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THE BRIGHTNESS OF THE STARS—THEIR DISTRIBUTION, COLORS, AND MOTIONS[1]

By Frederick H. Seares

From the summit of Mount Wilson there lies before the observer an amazing spectacle—not the panorama of valley and mountain nor the stars of heaven spread across the sky, but the seemingly innumerable lights that stud the floor of the valley—more convincing evidence even, than can be had during daylight hours, that the habitations of several hundred thousand human beings lie below. In the foreground is the city of Pasadena, and beyond, Los Angeles, with the intervening space almost continuously illuminated; and still more remote, the lights of adjoining towns and villages reach out in slender lines that here and there touch larger groups along the coast. From mountain-foot to coast-line, a stretch of more than thirty miles, there is scarcely a break in the continuity of these conspicuous evidences of human life and activity. In other directions there are many isolated groups, some including only a few tiny glittering points of light, others larger, tho more compact, but likewise isolated, except as the brilliant headlight of an electric train or the lights of motor cars, slowly threading their way across the valley, suggest and symbolize all the intimate relationships that knit together the life of modern towns and cities.

There is much in the spectacle to touch the imagination, but it is not the imaginative suggestiveness of the scene that demands our interest now, so much as a certain parallelism with the heavens above. Many things have been learned about the stars, but to understand them, to comprehend and make them a really vital part of our knowledge of the world about us, they must be pictured in terms of every-day experience, translated into language so familiar that we need give no thought to the medium in which the facts are set before us. On a black and moonless night, the glittering lights of the valley are not unlike a glorious constellation; and the analogies that may be traced between them and the distant stars should smooth away difficulties which otherwise would be encountered.

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[1] Fifth Adolfo Stahl Lecture, March 15, 1918.

1. The Fixed Stars—Early Conceptions

To the ancients the stars were the "fixed stars," distinguished from the wandering stars or planets by the fact that they hold unchanged their positions with respect to one another. The objects which for the Chaldean shepherd comprised the constellation of *Orion* still appear above the southern horizon during winter evenings, with the configuration they had 3,000 years ago. They were just glittering points of light securely attached to the surface of the celestial vault, whose daily rotation carried them about the stationary Earth from which he watched them rise and set and sweep across the sky.

And thus the stars remained, fixed, until two hundred years ago, when Halley, in 1718, showed that *Sirius*, *Procyon*, and *Arcturus* had perceptibly changed their positions with respect to neighboring stars. Previously there had been no evidence that the stars might be in motion, that the permanence of form so long attributed to the stellar firmament would one day lose its meaning.

As to the size and distance of the stars the ancient mind could only speculate. Copernicus in the 16th century said they must be very distant because they did not reflect the motion of the Earth in its path about the Sun. The phenomenon to which he referred is similar to what occurs when you move over the mountain top. The lights in the valley seem also to shift about, and if you watch attentively you will find they mimic every movement that you make, but with motions opposite in direction to your own. Walk a hundred paces toward the west and the lights in the foreground just below you shift perceptibly toward the east with respect to those farther off; return to the point from which you started and they promptly reverse their motions and retreat to their former places. And you will note that the shift of any given light depends upon its distance. For those nearest to you the motion is unmistakable. For more distant lights, tho perceptible, it is much less conspicuous; but beyond a certain point the unaided eye no longer sees the shift. The displacement is too minute to be detected without instrumental aid.

And just so, the stars should mimic the larger excursions of the observer in his annual motion about the Sun. But no such change of place had been detected, because, as Copernicus said, the stars are so very distant. His opponents, however, said this was only to be expected, for since the Earth did *not* revolve about the Sun, such a shift could not occur.

Nevertheless, the Copernican point of view slowly gained adherents, and the conviction gradually grew in the minds of men that a central sun surrounded by revolving planets is the correct conception of our solar system. And, finally, the precise and skillful measures by Bradley which led to the discovery of the aberration of light, put the matter beyond a doubt. The chances were shown to be overwhelmingly in favor of a motion of the Earth about the Sun; and yet there was no evidence of any corresponding change in the positions of the stars.

2. The Stars Are Suns—Extent of the Stellar System

The accuracy of Bradley's measures was such as to reveal any displacement as great as $2''$, and made it probable, for a certain star at least, that the actual shift did not exceed $0''.5$. The implications of this result are not at once apparent. A second of arc is an exceedingly small angle. To subtend such an angle an object, say a short rod, must be looked at from a distance of more than 200,000 times its length. The difference in direction between the two ends of a foot ruler seen from a distance of 40 miles is almost exactly a second of arc; and the diameter of a small coin, a ten-cent piece, at a distance of two and a fraction miles gives the same result.

Bradley's measures thus meant that the distance of even the nearer stars must be several hundred thousand times that between the Earth and Sun. Altho some conception of the magnitude of the universe had gradually been developing, his observations set a lower limit to its size, and showed that, at most, the Sun and all the planets could be but an astonishingly insignificant part of the stellar system.

Further, objects at so great a distance as the stars must possess luminosity of extraordinary intensity. Their intrinsic brightness must be enormously great, otherwise they could not be seen. The apparent brightness of any source of light, a distant star, or a light in the valley viewed from the mountain top, depends upon two things—intrinsic brightness and distance from the observer. Intrinsic brightness, in the case of ordinary lamps, is expressed in candle power. With increasing distance the apparent brightness rapidly diminishes, and from the mountain one is able to see in the remoter parts of the valley only those lights which intrinsically are most luminous. Conversely, with some notion of the distance of any light, it would be possible, roughly at least, to estimate its candle power. Thus from Bradley's figures it was a matter of easy arithmetic to calculate that, in the average, the stars must be of the same general order of intrinsic luminosity, and presumably also of the same order of size, as our own Sun. Actually, the differences from star to star are very great; nevertheless it was clear that all might properly be regarded as suns, or from another standpoint, that our own Sun could justly be ranked among the stars.

These conclusions have not yet reached their full development. Evidence of stellar motion was not available until the beginning of the 18th century, and it was more than a century after Bradley's observations, and only eighty years ago, that definite measures of a star's distance were first obtained.[1] The determination of stellar motions and distances, which thus began almost within our own generation, requires the utmost skill of measurement, and became possible only with the development of precise and sensitive instruments. In the meantime much attention had been given to the brightness of the stars as the only field of investigation that could throw light upon the great problem of the structure of the stellar system. If we were to observe and count the lights visible from the mountain, we could at least learn their number and their range of brightness. Combining these results with the directions in which the lights are seen, we could detect tendencies toward symmetry of arrangement, and easily distinguish the chaotic straggling village from one built in accordance with an orderly plan.

3. The Magnitude Scale

Ptolemy in his catalog which forms a part of the *Almagest* divided the stars visible to the unaided eye into six classes or magnitudes, according to their brightness. The system thus introduced 2000 years ago was extended by later observers; in the 19th century it was given precise definition, and is the one we use today. The magnitude is a unit used to express brightness, as the inch or yard is used for the expression of length and distance; but note that it measures a physiological perception, the sensation of brightness produced in the eye of the observer by the star's luminosity, and is not to be confused with the intensity or energy of the light causing the sensation.

Magnitudes increase numerically as the stars become fainter. The relation of magnitude and intensity, of sensation and stimulus, is not one of simple proportionality, but logarithmic in character. To produce the sensations measured by the magnitudes 1, 2, 3, 4, etc., the intensities must decrease in a geometrical progression, whose factor is 1/2.512..., and are thus proportional to 1, 1/2.512, $1/(2.512)^2$, $1/(2.512)^3$, etc. Simplifying the sixth term of this sequence we find its value to be exactly 1/100. Hence, two stars whose light intensities are to each other as one to a hundred differ in brightness by five magnitudes. This simple relation in round numbers is the definition introduced a generation ago which placed stellar photometry on a precise numerical basis. The factor 1/2.512..., the intensity-ratio corresponding to a difference of one magnitude, is a consequence of the definition. Its unwieldiness is of no disadvantage, for the simple reason that in practice it is not directly used.

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[1] For an account of stellar parallaxes and their measurement, see van Maanen's article in the preceding number of these *Publications*, page 29.

We are to remember, therefore, that magnitude is primarily a measure of sensation, while light-intensity expresses the stimulus producing the sensation; and that a ratio of about 1 to 2.5 in the intensity corresponds to a difference of one unit of the magnitude scale.

In undertaking measurements of any kind we must be provided with a scale, something like the yardstick with which we measure lengths, or the standard weights used in the ordinary operation of weighing. The unit of brightness has been defined; but practically we require something more tangible than a general statement of a dozen words or more. For the actual measurement of stellar brightness we have selected certain stars near the North Pole, and by methods that need not be described here have determined the magnitude of each. These stars are analogous to the standard weights with which other objects may be compared; and, similarly, we find the brightness of any star by comparing it with the standards of known magnitude at the Pole. The brightness of many thousand stars has been thus determined. Altho standard magnitudes in other parts of the sky are often used, the principle remains the same.

4. The Number of the Stars

What conclusions may be drawn from measurements of stellar brightness? What light do they shed upon the problems of the stars? In Ptolemy's catalog the brightest stars were assigned the magnitude one, but in the modern readjustment of the scale they are more nearly of zero magnitude. Roughly we may take the sixth magnitude as the limit of unaided vision, while with great telescopes such as the 60-inch reflector on Mount Wilson, a photographic exposure of 3 or 4 hours will reach the 20th magnitude.

The range of 20 magnitudes thus within our reach is not an adequate expression of what we really have to deal with. The extremes of intensity, or of energy, are vastly more impressive. Since an interval of 5 magnitudes corresponds to an intensity ratio of 1/100, 10 magnitudes implies a ratio of (1/100)x(1/100) or 1/10,000; and it follows, similarly, that stars of zero magnitude have an intensity 100,000,000 times greater than those 20 magnitudes fainter. The diversity in the light of the stars is therefore very great. The extent to which differences in distance contribute to this result will be discussed later.

Even the casual observer recognizes that the faint stars are much more numerous than the brighter objects. For the telescopic stars our counts are not complete, but with allowance for this defect, the totals, for the whole sky, of objects brighter than each successive magnitude are as shown in Table I.[2] These results are subject to revision, the numbers in parentheses being very uncertain, altho their general order of magnitude is probably correct.

TABLE I

TOTAL NUMBERS OF STARS BRIGHTER THAN EACH UNIT OF THE HARVARD SCALE OF VISUAL MAGNITUDES

MAGNITUDE	NO. OF STARS	RATIO	MAGNITUDE	NO. OF STARS	RATIO
0	3		10	380,200	
		3.7			2.7
1	11		11	1,026,000	
		3.5			2.5
2	39		12	2,588,000	
		3.4			2.3
3	133		13	5,894,000	
		3.4			2.2
4	446		14	13,120,000	
		3.3			2.1
5	1,466		15	27,540,000	
		3.2			2.1
6	4,732		16	57,150,000	
		3.2			(1.9)
7	15,000		17	(107,200,000)	
		3.1			(1.8)
8	46,240		18	(197,200,000)	
		3.0			(1.7)
9	139,300		19	(335,000,000)	
		2.7			(1.6)
10	380,200		20	(530,900,000)	

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[2] Derived from *Gröningen Publication*, No. 27, p. 63. Beyond the 16th magnitude the results are extrapolated, but receive general confirmation thru uncompleted investigations at Mount Wilson.

The numbers of faint stars seem astonishingly large. Why should they be so greatly in excess of the brighter stars? At first we knew nothing of differences in size and luminosity of individual stars nor anything of their distribution in space. It was natural, therefore, to make tentative inquiries based on the assumption that, intrinsically, all stars are equally luminous and uniformly distributed throughout an endless space. The fainter stars were accordingly fainter because they were farther away. Initially, this hypothesis was as plausible as any other; and it is interesting to see what it yields for the total numbers of stars down to the limits fixed by each unit of magnitude.

It is not difficult to show that the total to any magnitude will be $(2.512)^{3/2}$ or 3.98 times the total to the next brighter magnitude. In fact, this result holds even when the individual stars are not all intrinsically of the same luminosity, provided the mixture of objects of different brightness is the same at all distances. Anything like a uniform distribution of stars throughout space, therefore, necessarily implies the existence of enormous numbers of faint stars. It is like the old problem of shoeing the horse, in which the cost of each succeeding nail is doubled. The total is an incredible sum; but with the stars the numbers increase much more rapidly, for with each succeeding magnitude the totals are quadrupled instead of being only doubled.

Examining the ratios of adjacent totals found by actual counts, which are also given in Table I, we find that in no case do they reach the theoretical maximum of 3.98. For the brighter stars they fall little short of the maximum, but near the lower limit of brightness now accessible to observation the ratio is only half that calculated on the hypothesis of uniform distribution.

5. Limitation of the Stellar System

What may we conclude from this result? Obviously that the stars are not uniformly scattered throughout space, that with increasing distance the number in a given volume becomes less and less.

In the vicinity of the Sun the stars are most numerous, but in the remoter regions they thin out gradually. From the progression of the totals given in Table I it is evident that there are vast numbers of still fainter stars, invisible even with our most powerful telescopes; but beyond some limit of distance there seem to be no stars belonging to the aggregation to which our counts refer. If the decrease in the ratio for successive totals *continues undiminished* beyond the 16th magnitude, there can be few if any stars fainter than the 28th or 30th magnitude;[3] but the assumption involved is very precarious indeed. Probably there is no definite lower limit; but perhaps we may safely say that the total of all stars fainter than the 30th magnitude is relatively very small.

From simple counts of the stars for each interval of magnitude we learn that our stellar system is limited, and that the stars gradually thin out as we approach its boundaries. We have assumed that the mixture of stars of different intrinsic brilliancy is everywhere the same, and we have neglected nothing but a possible loss or scattering of light in its passage thru space. The distant lights of the valley are obliterated when the air is filled with mist and haze, while those still visible are much decreased in brightness. Thru the loss of light in the dust-laden atmosphere the content of the field of vision shrinks to a fraction of its normal size and brilliance. Were light absorbed or scattered in interstellar space, an infinite universe might appear as our own really does; but from independent evidence it seems practically certain that such absorption as may exist is insufficient or not properly distributed to affect appreciably our conclusions.

6. FORM OF THE STELLAR SYSTEM—RELIABILITY OF RESULTS

Other results may also be derived from counts of stars. Since the time of the elder Herschel it has been recognized that the Milky Way is the backbone of our stellar system. Stars of all degrees of brightness are more numerous in its vicinity, and it is clear that the galactic plane must be of great importance in all stellar problems.

We arrange our counts in zones parallel to this plane by supposing circles to be drawn about the celestial sphere parallel to the Milky Way, at intervals say of 10°. Counting the stars of each interval of magnitude between adjacent circles, we find that zones equidistant from the Galaxy, north and south, contain approximately the same numbers of stars. The plane thru the Milky Way is therefore a plane of symmetry, and to simplify results we average the totals for such pairs of equidistant zones. We thus obtain Table II.

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[3] This is not intended to apply to star clusters, spiral nebulae, or possible aggregations of stars similar to our own galactic system but disconnected from it and very distant.

TABLE II

Total Numbers of Stars per Square Degree Brighter than a Given Magnitude at Different Distances from the Milky Way

MAG.	GALACTIC LATITUDE							
	5°	15°	25°	35°	45°	55°	65°	80°
8.5	3.3	2.4	1.9	1.5	1.4	1.3	1.3	1.2
9.5	10.4	7.3	5.5	4.4	3.9	3.7	3.5	3.4
10.5	29	20	14	11	10	9	8	8
11.5	81	53	36	28	23	21	19	17
12.5	209	130	86	63	51	44	39	35
13.5	507	301	192	135	105	88	75	64
14.5	1138	676	398	267	200	160	132	112
15.5	2483	1479	800	514	369	282	229	195
16.5	5495	3162	1585	933	661	501	398	331
17.5	12020	6607	3090	1660	1148	871	692	550

The first column, with each successive column, gives for the different zones results analogous to those for the whole sky in Table I. The numbers of stars, however, now refer to a unit area of one square degree. The distance of the middle of each zone from the galactic plane, its galactic latitude, is at the head of the column.

What first strikes attention is the crowding of stars near the Milky Way. For all magnitudes the numbers increase with decreasing distance from the galactic plane, but for the fainter stars the crowding is most pronounced. This is clearly shown by comparing the ratios of the numbers in the 5° zone with those at 80°. Such a ratio is called the galactic concentration for the magnitude to which it refers. The increase in the concentration, as fainter and fainter stars are included in the totals, is strikingly shown in Table III.

TABLE III

Galactic Concentration for Different Limiting Magnitudes

MAG.	GALACTIC CONCENTRATION	MAG.	GALACTIC CONCENTRATION
2.5	2.4	10.5	3.7
3.5	2.2	11.5	4.7
4.5	2.2	12.5	6.1
5.5	2.1	13.5	8.0
6.5	2.2	14.5	10.1
7.5	2.3	15.5	12.7
8.5	2.6	16.5	16.6
9.5	3.1	17.5	21.9

Here again the numbers are subject to some revision, particularly for the fainter stars, but in the main they must be substantially correct. The bright stars near the Milky Way are only two or three times as numerous as those near the poles, but, as fainter stars are added, the ratio increases until at magnitude 17.5 the totals near the Galaxy are more than twenty times those in the higher latitudes.

TABLE IV

Ratios of Total Numbers of Stars Brighter than Successive Units of Magnitude

MAG.	GALACTIC LATITUDE							
	5°	15°	25°	35°	45°	55°	65°	80°
8.5								
	3.2	3.0	2.9	2.9	2.8	2.8	2.7	2.7
9.5								
	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.3
10.5								
	2.8	2.7	2.6	2.5	2.4	2.4	2.3	2.2
11.5								
	2.6	2.5	2.4	2.3	2.2	2.1	2.1	2.0
12.5								
	2.4	2.3	2.2	2.1	2.1	2.0	1.9	1.8
13.5								
	2.2	2.2	2.1	2.0	1.9	1.8	1.8	1.8
14.5								
	2.2	2.2	2.0	1.9	1.8	1.8	1.7	1.7
15.5								
	2.2	2.1	2.0	1.8	1.8	1.8	1.7	1.7
16.5								
	2.2	2.1	2.0	1.8	1.7	1.7	1.7	1.7
17.5								

Examining now the ratios of adjacent numbers in each column of Table II, which are analogous to the corresponding ratios in Table I and are separately listed in Table IV, we find that near the Milky Way they are larger than the averages for the whole sky, while near the galactic poles just the reverse is true.

The interpretation of these facts requires only an extension of the result derived from Table I. The numbers of faint stars increase much faster in the Milky Way than they do in higher latitudes, but even in the Galaxy itself the increase is far below that corresponding to a uniform distribution throughout space. The stars therefore thin out in all directions, but much more rapidly toward the poles of the Milky Way than in the Milky Way itself. This is equivalent to saying that the great bulk of the stars is contained in a much-flattened spheroidal region of space, whose greatest extension lies in the plane of the Galaxy.

In a general way these results have long been known, altho certain details, notably the rapid increase in the galactic concentration, have only lately been placed beyond doubt. The conclusions are based upon simple statistical discussions, but it should not be overlooked that the counts are assumed to have been made to accurately determined limits of brightness; thus the existence of a reliable scale of magnitudes is presupposed. Unless the brightness of the standard stars used for the determination of the magnitudes of the great mass of stars is precisely known, the conclusions will be vitiated and rendered uncertain to a corresponding degree. And herein has lain the difficulty. It is only recently that the magnitude scale has been extended to the fainter stars with such precision as would justify confidence in the results. The serious obstacle has been the enormous range in the intensity of the light of bright and faint stars which had to be compared with one another. We have seen that a range of 20 magnitudes corresponds to an intensity ratio of 1 to 100,000,000; that for 17.5 magnitudes, the interval over which we have reliable counts, is 1 to 10,000,000. The distance from San Francisco to Chicago is approximately 2,000 miles or about 10,000,000 feet. The problem therefore is analogous to that of comparing the length of a foot ruler with this continental distance, but much more difficult, for the percentage error in measurements of brightness is very much larger than that affecting measurements of length.

7. The Color of the Stars

The results described in the preceding sections are by no means all that may be derived from measures of stellar brightness. Thus far we have been concerned with the light as it appears to the eye; but starlight, like sunlight, is a mixture of many colors, and it requires only the most casual observation to learn that the mixture cannot in all cases be the same. For example, *Vega* and *Sirius* are white or bluish white, *Capella* is a golden yellow, while *Betelgeuze*, *Antares*, and *Aldebaran* have various hues of red. To produce this sequence of colors as seen by the eye, the mixtures in the several cases must contain less and less of blue and violet light, and hence an increasing preponderance of red and yellow. With *Antares*, for example, the excess of red is such that the mixture of all the colors radiated is the deep ruby tint which makes the star so conspicuous an object in the summer sky.

The color of a star, as we see it in the heavens, therefore depends upon the relative amounts or intensities of the separate colors which it radiates. Were it possible to measure the sensation of brightness produced by each of these, just as we have already done for the mixture of them all, we should be able to find a numerical expression for the color of the star. Practically, the conditions are such that if we measure the relative intensities of any two of the constituent colors which are sufficiently separated in the spectral band, such as blue and yellow, or the relative amounts of different groups of colors, say of blue and violet as compared with yellow and orange, we shall be able to determine the resultant color as it appears to the eye.

The extension and development of the methods of measuring brightness thus suggested must now be described; but first we may consider how important a knowledge of the colors is likely to be.

The color of the light radiated from a luminous source is intimately connected with temperature. No one who has watched a piece of iron when heated thru all the shades of red to white heat can fail to recognize the closeness of this relationship. Moreover, with the stars at least, temperature conditions immediately suggest the processes of growth and decay, for it is improbable, and quite out of accordance with usually accepted ideas, that the temperature of a star should remain constant. We are certain, therefore, to obtain from observations of color important information as to the physical condition of a star and the stage of its development. We shall also find important relations between the color of stars and their positions with respect to the Milky Way, so that the adaptation of photometric methods to the measurement of colors must also add to our knowledge of the structure of the stellar system.

No one needs now to be reminded of the significance of observations made with the spectroscope; but spectrum analysis is only a refined method of color analysis. Photometric measures of color, therefore, overlap to some extent the field of spectroscopy. Really they supplement spectroscopic observations, for they may be applied to stars too faint for examination with the spectroscope.

8. Photographic and Photovisual Magnitudes

Since magnitude is primarily a measure of physiological sensation, it depends not only on the star and its distance, but also upon the perceptive peculiarities of the eye. The light sent out by a star includes a wide range of wave-lengths or colors to which the eye is not equally sensitive. The visual sensibility is a maximum in the yellow-orange region of the spectrum, and falls gradually in either direction toward the red and violet.

The relation which makes an interval of five magnitudes the equivalent of an intensity ratio of 1 to 100 naturally applies to those colors which rouse the sensation of luminosity. Since, in any given star, these occur with unequal intensities, the resultant sensation is very complex, and, owing to differences in different eyes, cannot be sharply defined. The measure of the resultant visual sensation is called a visual magnitude, and refers to the normal eye. To one who is color blind the brightness of the star may be very different.

Since a definite numerical relation connects magnitude interval and intensity ratio, magnitudes may be calculated independently of any visual sensation, provided the star's effective intensity can be determined. The photographic plate provides the required means of measuring intensities, and we have accordingly systems of magnitudes unrelated to the eye and the measurement of sensation, except that they are made to agree as closely as possible with the visual scale of magnitudes.

The ordinary photographic plate is restricted in its sensibility to blue and violet light. For all ordinary exposures the impression produced by yellow, red, and orange is negligible. Such a plate therefore measures mainly the intensity in blue and violet, and, expressed in magnitudes with the aid of the fundamental relation, the result is called a photographic magnitude.

Every photographer is familiar with the so-called isochromatic plate. Its name would indicate that it is equally sensitive to all colors, but such is not the case. Altho affected by yellow and orange, it is far more sensitive to blue and violet. Exposed behind a suitable yellow filter, which transmits freely the former group of colors but only slightly the blue and violet, it can be used to measure the intensities of those colors which affect the eye. The combination of plate and filter is practically an equivalent of the normal eye. Numerically the resulting photovisual magnitudes are sensibly the same as visual magnitudes, but otherwise have certain advantages over the visual system. They can be more reliably and more rapidly determined, and, by using a reflecting telescope and a standard brand of plate and filter, the results are sensibly free from the kind of error which in visual magnitudes arises from peculiarities in the eye.

9. COLOR INDEX. THE EXPOSURE RATIO

Of the three kinds of magnitudes, visual and photovisual are a measure of intensity mainly in the yellow region of the spectrum, while photographic magnitude measures the blue and violet. A knowledge of photographic and visual magnitudes for the same star therefore tells us the relative amounts of blue and yellow light sent out by that particular object, and hence indicates its color. For the actual measurement of star colors we introduce a quantity called the color index, defined by the equation

$$\text{Color-Index} = \text{Photographic Mag.} - \text{Visual Mag.}$$

It is a matter of convention as to the particular intensity assumed to correspond to the zero of photographic magnitude, and for convenience it is determined in such a way that for white stars photographic and visual magnitudes are equal. Such objects therefore have a zero color index. A red star, being deficient in blue and violet light, is faint photographically, altho relatively bright in light to which the eye is strongly sensitive. Its photographic magnitude is therefore numerically greater than its visual magnitude, and its color index is accordingly a positive quantity, which for the reddest stars amounts to about two magnitudes. Conversely, for blue stars the color index is negative, but never very large, the extreme value being about -0.4 magnitudes. When once the indices corresponding to known colors have been determined, observations of magnitudes afford a very useful means of measuring color.

The photographic plate can be used in quite another way to measure color. The isochromatic plate in conjunction with a yellow filter, as we have seen, is most strongly affected by yellow light, and may be said to produce a "yellow" image. Without the filter, its sensitiveness to blue and violet is relatively so great that the image is essentially "blue." To measure the color of any star, we determine the ratio of the exposure times producing "blue" and "yellow" images of equal size. Obviously this ratio must differ for different mixtures of blue and yellow light, and can therefore be used as an indication of the star's color. The result is called the exposure ratio (exposure to blue *divided by* exposure to yellow).

It is not the purpose of this account to deal with the numerous applications of the spectroscope to stellar problems; nevertheless, to disregard them altogether would give an entirely erroneous impression, for at many points spectroscopic and photometric methods are very closely related. The earliest measures of star colors that we have were obtained from spectra and expressed in terms of spectral type or class. Thus the familiar notation B, A, F, G, K, M signifies not only the presence of certain typical groupings of lines and bands in the respective spectra, but also a certain regular progression of color, whose relation to color index is given below.

Spectral Class......	B	A	F	G	K	M
Color Index........	−0.4	0.0	+0.4	+0.8	+1.2	+1.6
Color Class........	*b*	*a*	*f*	*g*	*k*	*m*

We shall see presently that the relation of color to spectrum is not invariable, that stars with spectra showing the same number and arrangement of lines may differ appreciably in color. For certain purposes it is convenient to use a notation bearing a constant relation to color. The idea of color class is therefore introduced, with the symbols shown in the third line of the tabulation. Thus the letters *b*, *a*, *f*... *m* always correspond to the color indices which stand immediately above. At the same time, by virtue of the intimate relation between color and spectrum, they indicate the spectral class within narrow limits.

Altho spectral type is not an exact index of a star's color, the spectrum contains information from which the color could be accurately determined. Nevertheless direct measures of color, such as those given by the color index and the exposure ratio, are both convenient and important. Even for stars so bright that their spectra can be easily obtained, direct measures of color are more expeditious, while for the fainter objects, beyond the reach of the spectrograph, they are the only methods that can be applied.

10. Numbers and Distribution of Stars of Different Colors

Measures of color index and exposure ratio have only recently been undertaken. The data thus far obtained are accordingly very meager, and, for the most part, relate to the brighter stars.

In the meantime, spectral types have been determined for large numbers of stars, but these are necessarily restricted to the brighter objects. The colors found from spectra therefore relate to stars which are comparatively near, for in general, the brighter stars are much less distant than the fainter objects.

Counts of about 9,000 stars from the *Revised Harvard Photometry* give for the numbers of stars brighter than a specified magnitude the totals shown in Table V,[4] which is similar to Table I, but includes no stars fainter than magnitude 6.5.

TABLE V

NUMBERS OF STARS BRIGHTER THAN A GIVEN MAGNITUDE AND THE STAR RATIO FOR DIFFERENT COLORS

MAG.	B	A, F	G, K, M	ALL
2.5	22	23	28	73
	3.1	2.9	4.0	3.4
3.5	68	66	111	245
	2.7	3.2	3.5	3.2
4.5	184	211	393	788
	2.6	4.4	3.2	3.4
5.5	485	937	1264	2686
	1.7	4.1	3.2	3.3
6.5	821	3850	4103	8774

We note first that the ratios for adjacent totals given in the right-hand part of the last column, for all the stars together, agree sensibly with those of Table I. This in fact must be the case, for the six principal spectral classes here considered include the great majority of all the stars. The ratios for the G, K, M stars are the same as those for all classes together; but for the blue and white stars we find a very interesting result. The numbers for the B stars increase very slowly, while for the A, F stars the totals accumulate with unusual rapidity. The star-ratios show clearly the phenomenon in question; those for the B stars decrease rapidly, and apparently would become equal to unity near magnitude 7.5; below this limit the totals would be constant, and we should conclude that there are no B stars fainter than about magnitude 7.5. These objects therefore must thin out very rapidly with increasing distance.

For the A, F stars an opposite condition prevails. The ratios increase and actually exceed the theoretical maximum of 3.98, which we have seen holds for a uniform distribution in space; but they cannot increase indefinitely and, in fact, from some magnitude on must diminish, otherwise the ratios in Table I for all stars together could not decrease as they do.

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[4] Derived from *Harvard Annals*, **64**, 138, 140.

About 6,100 of the stars of Table V—those brighter than magnitude 6.25—have been classified in Table VI, according to spectral type and position with respect to the galactic plane. The tabular values are numbers of stars of each spectral class in regions of constant area whose mean distances from the Galaxy are given in the first column. For all classes the numbers increase with decreasing galactic latitude, but the behavior for different spectra is quite different.

TABLE VI

SPECTRUM AND GALACTIC LATITUDE—NUMBERS OF STARS[5]

GALACTIC LAT.	B	A	F	G	K	M	ALL
62°.3	37	296	156	128	378	101	1096
39.8	85	345	152	128	377	108	1195
21.6	227	539	200	170	459	126	1721
8.1	367	705	212	183	505	122	2094
SUMS	716	1885	720	609	1719	457	6106
GAL. CONC.	20.0	3.0	1.6	1.6	1.5	1.5	2.2

The B stars show a high concentration toward the Galaxy, while the K and M stars are much more evenly scattered and display but little crowding toward the Milky Way. The ratios for 5° and 80°—values of the galactic concentration—cannot be accurately determined from these data, but approximately are as given in the last line of the table, ranging from 20 for the B stars to only 1.5 for the K and M stars. The value of the galactic concentration in the last column for all spectral classes together, namely, 2.2, is in agreement with that in Section 6 found from quite different data (see Table III).

The behavior of the B stars, the bluest stars of all, is very peculiar. Apparently they comprise a very limited aggregation, closely confined to the plane of the Milky Way. The concentration of the A stars toward the Galaxy is marked, and apparently a large fraction of the fainter stars in low galactic latitudes belong to this class. The redder spectral classes are much more uniformly distributed, their galactic concentration being much below the average concentration for all the stars together.

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[5] Derived from *Harvard Annals*, **64**, 144.

TABLE VII

NUMBERS OF STARS OF DIFFERENT COLORS AT 0° AND 60° GALACTIC LATITUDE AND THEIR AVERAGE MOTIONS[6]

COLOR INDEX	NO. OF STARS		PROPER MOTION	PARALLACTIC MOTION
	0°	60°		
−0.43	45	19	2″.4	3″.5
−0.05	230	102	3.1	2.9
+0.34	167	110	7.8	8.9
+0.69	103	47	19.8	20.8
+0.96	63	63	10.0	8.6
+1.13	151	126	7.7	7.6
+1.26	116	83	5.0	4.9
+1.38	106	78	4.1	4.0
+1.52	50	21	4.1	4.6
+1.73	7	0	3.2	—

Very similar results are shown in Table VII, whose second and third columns contain the numbers of stars in the Milky Way and in galactic latitude 60°, corresponding to the observed color indices in the first column. The relations are more clearly shown by Fig. 1, which is based upon the data of Table VII. Here again we find the blue and white stars to be relatively more numerous in the Milky Way than in higher latitudes. For the bluest stars the numbers and curves are somewhat misleading, since they do not include objects brighter than the 4th magnitude, many of which belong to color class *b*. Table VII is therefore not altogether comparable with Table VI.

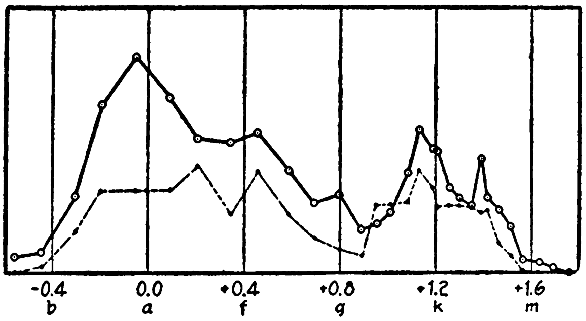

FIG. 1.—Vertical distances represent numbers of stars having the colors indicated at the bottom of the diagram. The continuous line shows the relatively larger number of blue and white stars in the Milky Way as compared with the number in regions 60° distant therefrom, the latter being indicated by the broken line.

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[6] Derived from *Göttingen Aktinometrie*, B, 34-37. The color indices have been reduced to the Mount Wilson color system.

The thinning out of the B stars and their apparent disappearance at about magnitude 7.5 raises a very interesting question as to the behavior of the faint stars in relation to color. Are there no blue stars to be found among them, or do such objects reappear at some point farther down the scale of magnitude; and what of the other color classes? The results thus far obtained are fragmentary but very suggestive.

In the region of the North Pole and the variable star S *Cygni*, we find that the color indices gradually increase as we consider fainter and fainter stars. Among the brighter objects we find zero and even negative values of the index; but with decreasing brightness the blue and white stars gradually disappear, so that at the 16th magnitude there are no color indices less than 0.5 magnitude. In these regions, at least, the faint stars belong to the redder color classes, and we find none bluer than class *f*. These results are illustrated in Fig. 2, in which the color indices are plotted as vertical distances, opposite the magnitudes of the individual stars. The curved lines along the lower boundary of each group of points show the gradual increase in the smallest value of the color index occurring among the stars of any given magnitude. At the 16th magnitude, for example, the bounding curves are one square distant from the zero line, and indicate, as already stated, an index of 0.5 magnitude.

For the region of S *Cygni* the results are less certain; those for the Pole have been confirmed by observations of the exposure ratio, and are well established. For faint objects in the star-clouds of the Milky Way determinations of color index and exposure ratio prove that here, at least, blue and white stars are to be found among the lower magnitudes; but we do not know at present

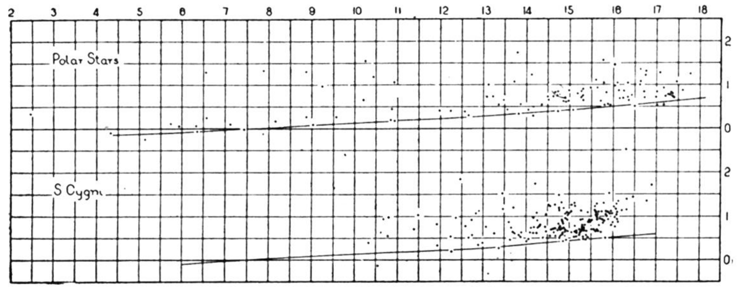

FIG. 2.—Horizontal distances are photographic magnitudes; vertical distances, color-indices. The smallest value of the index increases with the magnitude. In the two regions illustrated there are no blue or white stars among the fainter objects.

whether they are confined to the Milky Way itself, or whether there is a gradual change in the color of the faint stars with increasing distance from the Galaxy, thus providing a gradual transition to the conditions prevailing at the North Pole in galactic latitude 27°.

Our knowledge of the distribution of the various color classes over the face of the sky and among the objects of differing brightness is very much less than we should wish, and much less than it will shortly be. But we recognize that color stands in close relation to the detailed structure of the stellar system, and that the plan and organization of the system are to some extent reflected by the physical condition of the individual stars.

Before turning to other matters, another circumstance, clearly shown by both Tables VI and VII and by the curves of Fig. 1, needs a word of comment. The stars of color class *g* are seemingly much less numerous than those lying just above or just below in the scale of color. That this is true for various parts of the sky, may be seen from the numbers in each line of Table VI, or from those in the second and third columns of Table VII, or, better still, from the fact that both the curves of Fig. 1 approach the axis near the point marked *g*. The result is well established for the stars included in the counts, namely, all those to a certain limit of apparent brightness; but we must not incautiously conclude that it holds for all the stars in the sky, or for those within any specified distance. The relative numbers, as well as their absolute values, depend upon the way in which the stars have been selected. The question of selection is important, and to understand its influence in the present case, we must study the conditions that determine the brightness of a star as we see it in the sky.

11. ABSOLUTE MAGNITUDE—A MEASURE OF INTRINSIC BRIGHTNESS

Aside from the peculiarities of the eye, or of the photographic plate, two factors, distance and intrinsic brightness, determine the magnitude—the apparent magnitude—of a star. From the summit of the mountain the brightness of the lights in the valley depends upon their distance and their candle power; two lights of different candle powers may appear equally bright if that of higher power is more distant than the other. In the case of a star, to distinguish the influence of intrinsic brightness from that of distance, we use its absolute magnitude, a quantity analogous to candle power; and just as candle power is a measure of the intrinsic luminosity of a light viewed from a distance of one yard, so is absolute magnitude an expression of a star's intrinsic brightness when seen from a standard distance; it is what the star's apparent magnitude would be were it viewed from a distance corresponding to a parallax of $0''.1$.[7] Seen from this distance our Sun would be near the limit of visibility, with an apparent magnitude of 5; hence the Sun's absolute magnitude is 5. The absolute magnitudes of a group of stars therefore express the range in their actual brightness, with the same numerical relations between intrinsic intensity and absolute magnitude as hold for apparent intensity and apparent magnitude. A difference of 5 in the absolute magnitudes means that the light of one star is actually 100 times more intense than that of the other; similarly a difference of 10 corresponds to a ratio in intrinsic intensities of 1 to 10,000.

The three quantities—absolute magnitude M, apparent magnitude, m, and the distance expressed as a parallax, π, are connected by a simple equation

$$M = m + 5 + 5 \log \pi \qquad (1)$$

When any two of the three quantities are known, the third can be determined. Thus for stars whose distances and apparent magnitudes have been measured, absolute magnitudes can be computed from the formula, just as it would be possible to calculate the candle powers of distant lights in the valley, if we knew how far away they were and had measured their apparent brightness. Because of difficulties described in an earlier section, the distances of only a few objects have been directly measured, and these alone would tell us little of the real brightness of the stars.

Fortunately, as has been shown by Adams and Kohlschütter, it is possible to find the absolute magnitude directly from the spectrum, at least for all but the bluest spectral types. The relative intensities of certain pairs of lines, even in spectra of the same class, vary with the intrinsic brightness of the star; and by observing these critical lines, the absolute magnitude is quickly and accurately determined.

The classification and study of such absolute magnitudes as are now available lead to a very remarkable result. The bluest stars, on the average, are about 100 times more luminous than the Sun.

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[7] This is equivalent to saying that the radius of the Earth's orbit seen from the standard distance would subtend an angle of $0''.1$. A length of one foot at a distance of 400 miles subtends the same angle. The value of the standard distance in light years is 33.

Their mean absolute magnitude is not far from zero, and the individuals differ but little from the mean. A similar result holds for the A stars, but with a wider range in the individual values. For the redder spectral classes the behavior of the absolute magnitudes is that shown by Fig. 3, in which vertical distances represent numbers of stars having the absolute magnitudes shown at the top. With increasing spectrum or color the range of intrinsic brightness increases until for the M stars we find objects as bright as magnitude −3 and as faint as +13. Beginning with F there are for each type two values of the absolute luminosity which occur more frequently than any others, as is shown by the presence of two maxima in each of the curves. One of these is always near

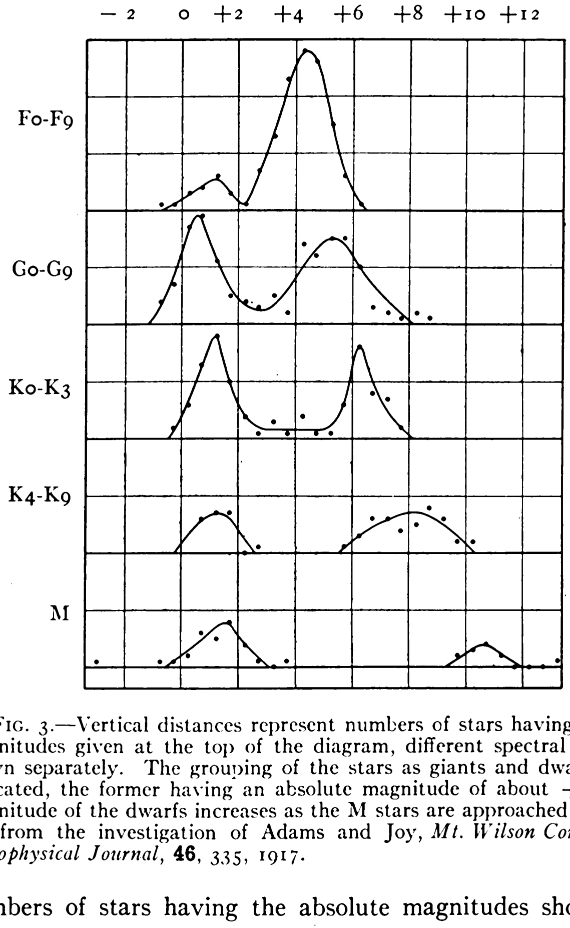

Fig. 3.—Vertical distances represent numbers of stars having the absolute magnitudes given at the top of the diagram, different spectral classes being shown separately. The grouping of the stars as giants and dwarfs is clearly indicated, the former having an absolute magnitude of about +1, while the magnitude of the dwarfs increases as the M stars are approached. The curves are from the investigation of Adams and Joy, *Mt. Wilson Contr.*, No. 142; *Astrophysical Journal*, **46**, 335, 1917.

absolute magnitude +1, while the other has the gradually increasing values, +4, +5, +6, +8, and +11 for each of the successive spectral intervals illustrated in the figure. For example, the two groups of G stars differ in their mean absolute brightness by nearly five magnitudes. For the M stars the difference is nearly 10 magnitudes, corresponding to a ratio of 1 to 10,000 in the intensities. In this case the two groups are clearly separated by an interval of about 6 magnitudes within which there are no M stars whatever.

Were we to measure the candle power of a large number of the lights in the valley, we should find a similar result; the arc lamps used for street illumination would be separated by a wide interval of brightness from the incandescent bulbs of a 100 candle power or more. The illustration here seems more or less trivial, but it would be less so had we no previous knowledge of the practice in illumination and were we, as in the case of the stars, unable to estimate approximately with the unaided eye the relative distances of the lights observed.

The very extraordinary splitting up of the redder spectral types into two sharply marked subdivisions has led to the introduction of the terms "giant" and "dwarf" stars. It is a remarkable and undoubtedly significant fact in the history of a star's development that objects having similar spectra should differ so greatly in absolute luminosity as do the giants and dwarfs. The similarity of spectrum and color means that the surface temperature, and hence the amount of light radiated from a constant area of the surface, is the same for both classes of stars; hence the range of 1 to 10,000 in the average absolute luminosities of giant and dwarf M stars must be attributed to differences in their linear dimensions. To radiate more light the giants must be larger than the dwarfs; and that their surfaces may be in the required ratio of 10,000 to 1, the diameters of the giants must be a hundred times those of the dwarfs.

But note what this implies—a ratio in the volumes of 1,000,000 to 1. What are we to infer as to the masses and densities of these stars? Without additional evidence the question cannot be answered; but we may make two extreme assumptions: (a) The densities of giant and dwarf stars are the same; the masses of the former will then be a million times those of the latter. (b) The masses are equal; the density of the giants can then be only one-millionth that of the dwarfs. The available evidence indicates that the second supposition is far nearer the truth than the former, and that the great difference in volume between giant and dwarf stars is to be explained by differences in attenuation of the material of which they are composed rather than by differences in the amount of that material.

The critical factor underlying these conclusions as to the linear dimensions of giant and dwarf stars is emphasized by the fact that they do not hold for the electric arcs and incandescent bulbs—the giants and dwarfs among the lights of the valley. A divergence enters because the stars compared have the same general type of spectrum, and hence nearly the same surface temperatures, while the lights represent wide differences in temperature; and, from candle power alone, we can conclude nothing as to the extent of the luminous surface emitting the light seen by an observer on the mountain.

12. RELATION OF COLOR TO ABSOLUTE MAGNITUDE

We have referred to the fact that the spectrum of a star is not an exact measure of its color, and that objects having the same type of spectrum may show appreciable differences in color. Investigations by several observers have shown that these differences are related to the absolute magnitudes of the stars, the more luminous objects being the redder.

Determinations of the exposure ratio for a group of giant and dwarf stars illustrate the nature of the dependence. The results are illustrated in Fig. 4, in which vertical distances represent the

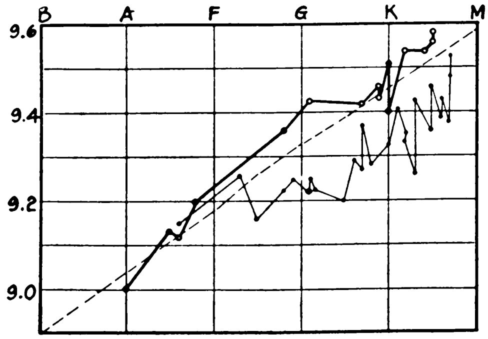

FIG. 4.—Variation of color with spectrum for giant (heavy line) and dwarf (light line) stars. Vertical distances represent logarithms of the ratio of exposure for blue light to exposure for yellow light necessary to produce the same photographic effect. For stars having G and K spectra the giants are appreciably redder than the dwarfs.

logarithm of the exposure ratio, while horizontal distances correspond to spectral types. The circles indicate giant stars and the points dwarfs. The dotted line gives the variation of the logarithm of the exposure ratio for the colors normally assumed in the Mount Wilson color system to correspond to the different spectral types, and was derived from the color indices and spectra of the Polar Standards of magnitude. None of the giants differ greatly from zero absolute magnitude, and the progression of exposure ratio with spectrum for these stars is fairly regular. The dwarf stars average 4 or 5 magnitudes fainter than the giants, and altho the scattering of the points is considerable, the change in the exposure ratio with spectral class, and the relation of color to absolute brightness is clearly enough shown.

Since the ratio is: exposure to blue *divided by* exposure to yellow, a large value of the ratio implies a deficiency of blue light, and hence an excess of red light. The giant stars are clearly redder than the dwarfs, as already stated, the difference, expressed in color index, easily amounting to half a magnitude. For the late A and early F spectra the color difference is inappreciable, and the diagram suggests that further observations may show that the curves for giants and dwarfs cross at this point, thus giving a reversal of the effect for the B stars.

13. RELATION BETWEEN THE DISTANCES OF STARS AND THEIR APPARENT MOTIONS

In an earlier section we have seen something of the difficulties encountered in attempting to measure directly the distances of the stars. A more expeditious method is to make use of equation (1), by means of which the parallax, π, can be calculated when the absolute and apparent magnitudes have been determined. Intrinsic brightness, as we have seen, can be derived from the spectrum for all but the bluer spectral classes, and apparent magnitude can be measured by the method outlined in Section 3.

This is the most valuable method that we possess for the determination of the distances of large numbers of individual stars; but it has only recently been developed, and in the meantime relations between the distance and apparent motions of the stars give valuable information as to the average distance of any particular class of stars, say those of the sixth apparent magnitude, or those having G-type spectra.

The principles involved are simple. Suppose we observe from the mountain, not the lamps that light the streets of a distant town, but those of the moving motor cars within its limits. These will be traveling here and there in all directions, with a considerable range of speed. During a given interval, say one minute, the direction in which each car is seen will change a certain amount. The average of all these changes in direction depends upon the average speed, in miles per hour, with which the cars are moving. Suppose that the average change in direction has also been determined for the motors of a second town, and assume, further, that the average speed per hour is in both places the same. The relative distances of the two towns from the observer can then be found. If the average change in the positions of the moving cars is the same, the towns are equally distant; and if one average is smaller than the other, the town to which it corresponds is the more distant of the two.

The total annual change in the direction in which a star is seen is called its proper motion. If we suppose that the average speed of the stars, in miles per second, is everywhere the same, it follows that the average proper motion of distant stars will be smaller than that of nearer objects; and by comparing the average motions of different groups of stars we can find their relative distances. Finally, from the motions of stars whose distances have been directly measured, we derive a relation between average proper motion and parallax which can be used to find the average distance of any group of stars whose motions have been observed.

By way of illustration, we have in the fourth column of Table VII the average proper motion during an interval of a hundred years, for each of the groups of stars whose mean color indices appear in the first column of the table. These numbers increase to a maximum and then decline again; and from them we infer that the stars showing the extremes of color are the most distant, while those of the intermediate color classes, with indices of about +0.7, are nearest to us.

There is another and even more important method of using the apparent motions of the stars to find the average distance of any class of objects. Suppose the observer on the mountain to walk along its top, as in an earlier illustration—toward the west, we assume, and with a known rate of motion. During a minute he will have moved say a hundred yards. In the meantime the lights in the valley to the south will apparently have shifted toward the east by a certain definite angle, whose value can be found by measurement. The problem of determining the distance of the lights is just that of calculating the distance from which a length of one hundred yards subtends an angle equal to the observed change in direction. If the lights are not in motion, observation of any one of them determines the distance of the town to which it belongs.

But suppose that we again observe the lights of the moving motor cars within the town. During the minute in which the observer walks the hundred yards, each motor moves a certain distance. Apparent changes in direction are produced by the observer's motion as before, but these are modified by the motions of the cars themselves. For some the eastward displacement is increased, for others, diminished; but for a large number of cars, moving at random, and with random speeds, the individual motions compensate each other and the average displacement toward the east is the same as tho the cars were all at rest. The distance of the town can therefore be calculated as accurately as before.

And thus we can compute the average distance of a certain group or class of stars when their individual motions are at random. The Sun and its attendant planets, moving thru space in a definite direction with known speed, carry with them the observer who, after an interval, measures the changes in direction of the stars. Their apparent motions are the result of the observer's change in position, combined with the motions of the stars themselves.

Each individual proper motion is analyzed into two components, one parallel to the motion of the Sun, the other perpendicular to this motion. The latter must be due entirely to the real motion of the star, but the former—the parallactic component as it is called—is produced partly by the motion of the star and partly by the motion of the Sun. For objects moving at random, the part due to the real motions of the stars will vary in amount, and sometimes will be in the same direction as the solar motion and sometimes opposite thereto. If, therefore, we form the average of the parallactic components for a large number of stars, their individual motions will compensate each other and the mean will be the same as tho the stars were all at rest. The result, which represents the effect of the observer's motion upon the direction in which the stars are seen, is the parallactic drift or motion of the group of stars observed, and corresponds to the eastward displacement of the lights produced by the change in the position of the observer on the mountain top.

The parallactic drift, combined with the known motion of the Sun, gives at once the mean distance of the group of stars observed. The method is not applicable to stars directly in the line of the observer's motion, but gives useful results for objects in other parts of the sky. The fact that he is in the midst of the stellar system, with stars on every hand, does not alter the problem essentially.

The mean parallactic drift for an interval of a hundred years is also given in Table VII for stars of different color index. The numbers vary inversely as the distances, and confirm our earlier conclusion as to the relative distance of the stars of different color. The *f* and *g* stars are nearest to us, and, occupying a smaller volume of space than the other color classes, we should expect them to be less numerous. This perhaps accounts for part of the deficiency in the numbers of these objects, to which reference has already been made. The matter is not altogether clear, however, for the smaller distances of these stars indicate that their mean absolute luminosities are below the average of the other color classes. The parallactic motions of the very red stars are of the same order of magnitude as those of the blue stars. The mean distances and luminosities of both these classes of stars must therefore be sensibly the same. By consulting Fig. 3 we see that this result apparently can be brought about only by excluding the dwarf K and M stars. It is probable, therefore, that our counts contain none of the dwarfs of these spectral classes. The F and G dwarfs, however, being appreciably brighter, may fall within the limit of apparent magnitude used in the selection of the data. This would account for the relatively low average luminosity of the F and G stars, but, on the other hand, would seem to indicate that the manner of selection had introduced a larger percentage of F and G stars than of K's and M's, i.e., giant stars plus some dwarfs, whereas, of the others, we have only giants. The actual number of the F's and G's included, as we have seen, is comparatively small and may therefore indicate a real deficiency for these spectral classes. These details show the artificial character of apparent magnitude as a limit in choosing data, and illustrate some of the disturbing effects of selection referred to at the end of Section 10.

14. Relation of Absolute Magnitude to Velocity of Motion

Recent accumulations of data bearing on the intrinsic brightness of the stars have brought to light a very significant relation between the absolute magnitude of a star and the speed with which it moves thru space. The nature of the relation is illustrated by Fig. 5, in which vertical distances represent absolute magnitudes, and horizontal distances the speed in kilometers per second with which the star is moving.

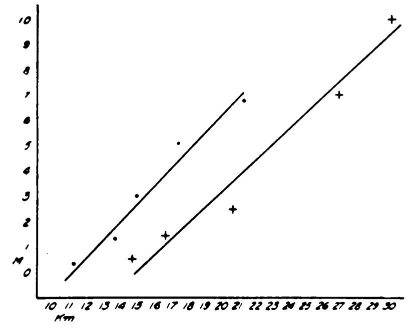

Fig. 5.—Variation of radial velocity (horizontal distances) with absolute magnitude (vertical distances). Points represent groups of stars having F and G spectra; crosses represent similar groups of K and M stars. From the investigation of Adams and Strömberg, *Mt. Wilson Contr.*, No. 131; *Astrophysical Journal*, **46**, 293, 1917.

The figure summarizes the results by Adams and Strömberg from about 1,300 stars, which were divided into two groups, one including F and G spectra (points), the other K and M spectra (crosses). For both groups there is a regular and sensibly linear increase in average radial velocity with increasing absolute magnitude. The gain in velocity amounts to about 1.5 kilometers per second for each unit of magnitude, and applies to both giants and dwarfs. The gap between the K and M stars of high and low luminosity is clearly shown between the upper two and the lower three crosses of the diagram. For the F's and G's, as shown by Fig. 3, the giants and dwarfs are not entirely separated, so that points in Fig. 5 are more uniformly spaced.

Finally, it will be noted that for the same absolute magnitude, the K and M stars appear to be moving with higher average speeds than the F's and G's.

The explanation of these relations and their significance as a mechanical feature of the stellar universe are not at present known. They may depend upon the masses of the stars, the smaller objects moving faster, on the average, than those of greater mass. On the other hand, the dwarfs may represent a later stage in the development which we commonly suppose each star to undergo, and there may be circumstances which cause a gradual acceleration of motion during the progress of the star's development. These are only suggestions; a properly grounded explanation must await the accumulation of further data.

15. THE SYSTEMATIC MOTIONS OF THE STARS

For two centuries we have known that the stars have motions of their own, but for only a short time has it been clear that they do not move at random. We now know many groups of stars which seem to be definitely organized physical systems, whose members travel thru space along parallel paths at a constant speed. The bright stars of *Ursa Major*, the *Pleiades*, a part of the Constellation of *Taurus*, a cluster in *Perseus* and one in *Scorpio*, and the B-type stars in the vicinity of *Orion*, not to mention many smaller aggregations, move as groups and thereby suggest that, besides their community of motion, they possess other characteristics in common. But these moving clusters comprise only a minute fraction of the total number of stars, and apparently have no close relation to the two great streams which appear to be one of the chief characteristics of the organization of our stellar system. The phenomenon of stream motion, which now requires our attention, is probably as significant a factor for stellar movements, as is the crowding of the stars in the Milky Way for the form of the stellar universe

Until 1904 it was commonly assumed, as in the preceding sections, that the vast majority of the stars might be regarded as moving at random. Kapteyn, however, showed that this is not even approximately the truth. The facts of the case can be learned by a study of proper motions, which, however, must be known with precision for a large number of stars well scattered over the sky.

The principle underlying the analysis is not difficult to understand. For a chosen region of the sky, with not too great an area, we count the numbers of proper motions having definite directions on the surface of the celestial sphere, and find a certain number toward the north, so many directed 10° east of north, so many 20° east of north, and, similarly, on around the circuit of 360°. Now let us construct a diagram with lines radiating from a central point at intervals of 10°, the length of each line being proportional to the number of proper motions in one of the specified directions; the ends of the radiating lines are then connected by a closed curve, and the result is called a velocity diagram.

For stars moving at random, and a solar system fixed with respect to the center of gravity of the system of the stars, the proper motions will be equally numerous in all directions, the radii which represent them will be equal, and the velocity diagram will be a circle. If we still suppose random motions for the stars, but assume the observer to be in motion, the velocity diagram becomes an oval with the point of origin for the radii no longer at the middle of the figure. The elongation of the oval, in direction and amount, and the position of the origin of the radii depend upon the observer's motion.

The result of analyzing the proper motions actually observed varies with the region of the sky considered, but is always a velocity diagram differing in a very characteristic way from those described above. The diagrams are no longer simple ovals, but usually pear-shaped figures, which can be accounted for only by supposing that the proper motions have a marked preference for two certain directions. A comparison of these preferential directions, which can be determined from the velocity diagrams of different regions, shows that they fall into two groups, and that the directions of each group converge and practically intersect in a single point which we call the apex.

Kapteyn showed that the phenomena are satisfactorily explained by supposing that the great majority of the stars belong to one or the other of the two great interpenetrating swarms whose motions, relative to the solar system, make with each other an angle of about 100°. The speeds are as 1.52 to 0.86, and the numbers of stars in each stream are as 3 to 2. The fundamental nature of the phenomenon is indicated by the fact that the motion of one swarm relative to the other is almost exactly parallel to the plane of the Milky Way. It is not to be supposed, however, that the hypothesis of two streams of stars is more than a first approximation to the systematic motions of the stellar system.

The question of systematic motions has also been investigated on the basis of velocities in the line of sight determined with the spectrograph. Here we use, not the number of motions, but the average value of the line-of-sight or radial velocity for the stars in each part of the sky. The results may be represented graphically in a manner similar to that used in preparing the velocity diagrams described above, except that now the radiating lines are not confined to a plane, but diverge in all directions into space, one for the direction of each region of the sky for which a group of radial velocities has been determined. The length of each radiating line is made proportional to the mean radial velocity of the stars selected in that direction, and thru the extremities of them all is passed a closed surface called the velocity surface. The variation in the distance of this surface from the point of origin within represents the variation in the average radial velocity from point to point in the sky.

In a recent investigation by Strömberg the data, including stars of F, G, and K spectral types, were divided into three groups according to luminosity, with mean absolute magnitudes of approximately 1, 2, and 6. The groups were discussed separately with results which are represented in Figs. 6, 7 and 8. The points in the three diagrams lie in the plane of the Milky Way. The full-line curves are intersections of the galactic plane with the smooth velocity surface best representing the observed average velocities. The dotted curves are similar intersections with the best-fitting symmetrical surfaces.

It will be noted first that the linear dimensions of the figure for the most luminous stars are smallest, and largest for that corresponding to the faintest stars. This agrees perfectly with the relation between absolute luminosity and speed found in the preceding section. Next it will be seen that the general characteristics of the three figures are the same. The symmetrical curves all have their longest axes in longitudes near 170°; in this direction, which agrees well with that of the stream motion, the average radial velocity is highest.

The curves corresponding to the velocity surfaces which more accurately represent the data are three-lobed, and the preferential directions of highest velocity no longer form a straight line, but are inclined at an angle which is smallest for the most distant stars. The arrows directed downward bisect these angles approximately,

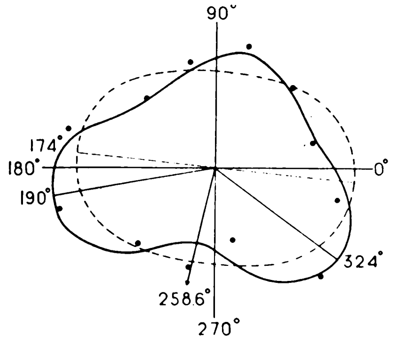

FIG. 6

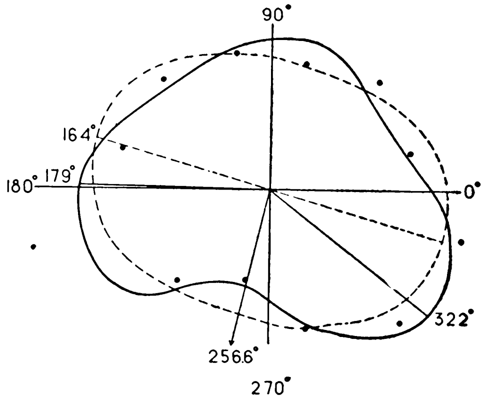

FIG. 7

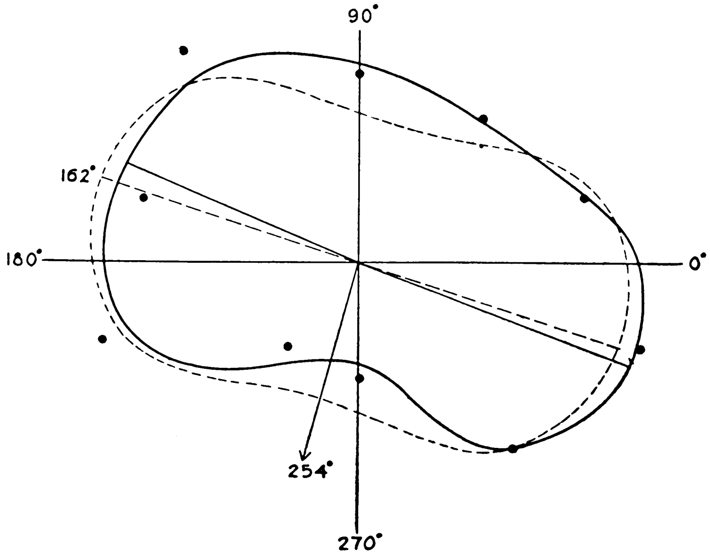

FIG. 8

FIGS. 6, 7, 8.—Intersections between the average radial-velocity surfaces and the galactic equator for three groups of stars—Fig. 6 for the stars intrinsically brightest and most distant, Fig. 8 for those intrinsically faintest and nearest, and Fig. 7 for the stars intermediate in luminosity and distance. The distances of the points from the intersection of the reference lines represent the average radial velocity in regions near the galactic equator. The projections of the longest axes of the surfaces are indicated by straight lines; the arrows indicate the position of approximate planes of symmetry perpendicular to the galactic equator. From the investigation by Strömberg, *Mt. Wilson Contr.*, No. 144; *Astrophysical Journal*, **47**, 7, 1918.

and indicate what for other reasons we believe to be the direction of the center of the stellar system. The axes of greatest mobility, therefore, seem to coincide better with a curve than with a straight line, and the directions of the preferential velocities are such as might be expected from a general circulation of the stars about the center of the system, with a strong tendency toward motion in the galactic plane; and the data possibly indicate that something of the sort is taking place.

From the radial motions we have determined the directions of the highest average velocity, while from the proper motions we have found the line in space along which motions most frequently occur irrespective of their size. Altho we might expect the resulting directions to coincide, the things investigated are quite distinct. The radial velocities confirm, in a general way, the existence of the two star streams, but at the same time suggest a modification of this explanation of the systematic motions of the stars, which may ultimately throw much light on the structure and mechanics of the universe.

16. SUMMARY

The main part of the preceding account deals with the brightness of the stars and with numerous questions connected with the determination of magnitudes. Simple counts of stars, if made to specified limits of a precisely determined scale of magnitudes, give much information about the form and extent of the stellar system, which appears to be a great flattened cluster, many thousand light years in diameter, with the Milky Way as a structure feature of first importance.

Observing the colors of the stars, either with the spectrograph, or by comparing their visual and photographic magnitudes, we learn that objects in different physical states are not scattered at random throughout space, but show a characteristic arrangement with respect to the galactic plane.

From determinations of stellar distance and apparent magnitude, we find that the stars display an extraordinary range of intrinsic brightness. Occasional objects are 10,000 times as luminous as our Sun, while, at the other extreme, there are probably stars with only 1/10,000 part of the solar luminosity.

All the blue and white stars, intrinsically, are intensely bright, but for the redder color classes we find the remarkable subdivision into giants and dwarfs, with wide differences, not only in absolute magnitude, but perhaps also in density.

We also find important correlations of absolute magnitude with color and with the velocity of motion thru space; and finally, we learn that the stellar system represents a high degree of organization in its motions, as well as in its form and structure.

Mount Wilson Solar Observatory,
March, 1918.

THE PROBLEM OF MARS

By W. W. Campbell

The work of the great Italian astronomer, Schiaparelli, on the surface features and physical conditions of the planet *Mars*, in the years 1877-1892, may be said to constitute a unique chapter in the history of that subject. If the astronomers of today were asked to name Schiaparelli's successors in the Martian field of investigation, they would unanimously and without hesitation say Professor William H. Pickering and Professor Percival Lowell. Pickering began to observe *Mars* systematically as early as the year 1890, and he is still studying that planet, as enthusiastically as ever, from a splendid location in Jamaica. Lowell's first contribution to the subject appears to have been made in his lecture before the Boston Scientific Society, on May 22, 1894 (published in *The Boston Commonwealth* of May 24, 1894), in which he said—"The most self-evident explanation from the markings (canals) themselves is probably the true one; namely, that in them we are looking upon the result of the work of some sort of intelligent beings.* * * * The amazing blue network of *Mars* hints that one planet besides our own is actually inhabited now.* * * * We stand on the threshold of a knowledge of our closest of kin in the world of space of the most important character." Lowell went directly from the lecture room in Boston to the new observatory at Flagstaff, Arizona, and began his distinguished career as an observer of *Mars* on May 31, 1894. This career was terminated by his lamented death in 1917.

Pickering's observations of *Mars* have thus extended thru a period of twenty-seven years, and Lowell's thru a period of twenty-three years; an average of twenty-five years.